

Requirements for Simulating Space Radiation With Particle Accelerators

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ABSTRACT

Interplanetary space radiation consists of fully ionized nuclei of atomic elements with high energy for which only the few lowest energy ions can be stopped in shielding materials. The health risk from exposure to these ions and their secondary radiations generated in the materials of spacecraft and planetary surface enclosures is a major limiting factor in the management of space radiation risk. Accurate risk prediction depends on a knowledge of basic radiobiological mechanisms and how they are modified in the living tissues of a whole organism. To a large extent, this knowledge is not currently available. It is best developed at ground-based laboratories, using particle accelerator beams to simulate the components of space radiation. Different particles, in different energy regions, are required to study different biological effects, including beams of argon and iron nuclei in the energy range 600 to several thousand MeV/nucleon and carbon beams in the energy range of ~ 100 MeV/nucleon to ~ 1000 MeV/nucleon. Three facilities, one each in the United States, in Germany and in Japan, currently have the partial capability to satisfy these constraints. A facility has been proposed using the Brookhaven National Laboratory Booster Synchrotron in the United States; in conjunction with other on-site accelerators, it will be able to provide the full range of heavy ion beams and energies required. International cooperation in the use of these facilities is essential to the development of a safe international space program.

I. INTRODUCTION

Exposure of humans to space radiation, whether part of International Space Station, crews on spacecraft voyaging to other planetary surfaces, or colonists on other solar system bodies, implies acceptance of a radiation risk. There are several ways of quantifying this risk as the probability of deleterious health effect due to ionizing radiation, including: cell death, resulting in nausea, vomiting, or other immediate (“acute”) effects, and cell changes leading to one of several types of cancer, or other, delayed health effects.

The important components of the space radiation environment are: the protons trapped in the Earth’s magnetic field (“Van Allen belts”), the proton component of energetic solar particle (SPE) events, and galactic cosmic rays (GCR). Outside the protection afforded by the Earth magnetic field and atmosphere, the main penetrating components of ionizing space radiation are protons (and some heavier particles) emitted in the course of SPE events, and protons and the energetic nuclei of heavier elements (also known as HZE – high atomic number Z and energy E – particles) that constitute GCR.

The SPE proton intensities can increase by four or five orders of magnitude within a few hours during a solar disturbance. In an unshielded or lightly shielded environment, SPE particle fluxes have the potential to cause acute radiation effects, but several techniques, such as seeking refuge in a well shielded “storm shelter”, can be used to keep the dose from SPE particles within acceptable limits.

HZE particles, whose fluxes change only slowly during the 11-yr solar cycle (1,2), present new and significant problems for radiation protection, that have not yet been resolved. Unlike SPE, the GCR appear as a low level background exposing the astronaut 24 hours each day requiring shielding during normal mission activity. Much less is known about the interactions of high energy nuclei with matter and the associated biological response (3) than is known for protons. Although the intensity of the GCR are low their accumulated exposure is a limiting factor in long-term space operations.

Human crews engaged in the exploration of space will also be exposed to weightlessness. The effects of radiation exposure thus need to be considered in the context of the physiological perturbations caused by weightlessness. Removal of the force of gravity results in structural and functional changes, especially in weight-bearing muscle, bone, and connective tissue. Changes also occur during space flight in endocrine, hematological, immunological, metabolic, nutritional and gastrointestinal, renal, sleep, biological rhythms, and temperature regulation; changes in pharmacokinetics and pharmacodynamics may further confound crew health care. Changes in immune function may be related to living in a “closed environment” -- the space habitat, the effect of stress during launch or landing, inhibition of white cell maturation due to microgravity or other factors.

Monitoring of crew exposures has been a normal part of the space program since the Gemini missions. Dose rates in the Apollo mission ranged from 0.22 to 1.27 mGy/day and the Skylab ranged from 0.54 to 0.86 mGy/day. Average crew dose rates on the Shuttle and space station MIR have been measured to be in the range of approximately 0.03 to approximately 2.5 mGy/day, depending on altitude and inclination (4,5). For the purposes of radiation protection, average quality factors, Q, have been evaluated using measured distributions of linear energy transfer (LET) and the dependence of Q on LET. In low Earth orbit, average values of Q are in the range of 1.4 to 3 (4,6); for the GCR component, the range of values is between 4 and 6.3 (4).

There are large uncertainties associated with estimation of the risk from long-term exposure to HZE (3,7). A Task Group of the US National Academy of Sciences - National Research Council (NAS/NRC) recently estimated (3) the resulting uncertainties to be within a factor of 4-15, i.e., the actual risk to astronauts on Space Station or exploration missions may be 4-15 times greater or 4-15 times smaller than predicted on the basis of the best currently available data and methods. According to this estimate, there are four sources of correlated uncertainty that need to be considered in estimating the accuracy of risk predictions:

- the uncertainty in the number, kind and energy of particles predicted to be along the spacecraft trajectory
- the uncertainty in the number, kind and energy of particles predicted within any shielded space environment (spacecraft, Station, planetary surface, etc.) and inside the tissues of crew members
- the uncertainty in the relationship between risk endpoint (e.g., excess cancer) and the calculated dose equivalent in the space environment, due to the coarseness of the “dose and dose rate effectiveness factor (DDREF)” estimates
- the uncertainty in the quality factor due to the significantly different biological effects for equal doses of different HZE particles with different LET.

The biological factors account for the bulk of the problem, and their uncertainty acts to amplify the smaller uncertainties in the physical environment and the shielded environment.

II. THE NASA SPACE RADIATION RESEARCH PROGRAM

A substantive research program is currently sponsored by NASA, with collaboration of other national and international agencies, using ground-based simulation of space radiation to develop the radiobiological knowledge required to predict risk from HZE particles accurately enough to define radiation limits for the human exploration in space. A road map for accomplishing the program vision of assuring a permanent human presence in space is shown schematically in Figure 1. The basic knowledge, required to answer the critical questions, is obscured by uncertainties. In order to acquire this basic knowledge and reduce

uncertainties in risk prediction, the strategies to be followed are: (1) simulate space radiation on the

FIGURE 1

ground, where studies can be performed most cost-effectively; (2) take advantage of available space platforms, such as robotic precursor missions; (3) validate predictions based on ground-based science on Space Station and other space platforms (e.g., Shuttle), to determine interaction of radiation with weightlessness; and, (4) develop countermeasures to mitigate radiation risk.

The program is intended to deliver risk management tools for Space Station as well as for deep space exploration. Risk management under ALARA requires that action levels be established at radiation exposures that are well below the maximum permissible limits. Action levels are required at the design stage of space missions as well as during mission operations. At the design stage, the program will provide requirements for warning and forecasting, provide tools for the optimization of shielding, and resources for implementation of biomedical countermeasures. Operational decisions are implemented by means of flight rules that specify radiation monitoring and personnel dosimetry, responses to unplanned radiation exposures (e.g., during a solar disturbance), responses to radiation monitoring and warning, scheduling of EVA, tours of duty, etc.

A list of critical questions in support of humans in space was developed in 1992 by the Aerospace Medicine Advisory Committee of the NASA Advisory Council (8), and subsequently revised by the Space Radiation Health Program Discipline Working Group. These critical questions addressed the nature of the space radiation environment; the properties of nuclear and atomic interactions of high-energy charged particles of space radiation with matter; the probabilities, characteristics and storage of molecular and cellular damage in a living organism, and their correlation with the probability of subsequent carcinogenic effects; the use of animal models to extrapolate probabilities of radiation risk to humans in space and to develop protection against it; and, finally, the evaluation of human radiation risk, including carcinogenesis, damage to the central nervous system, and genetic and developmental detriments.

The Radiation Protection Program is divided into three phases, covering short-term, intermediate-term and long-term progress. The near-term phase is intended to exploit currently available science to identify risks accurately. The priorities of this phase of the program are: identify all the risks from space radiation; provide accurate estimates of the uncertainties in risk prediction; and, lay the scientific and biomedical groundwork required to reduce uncertainty and develop radiation countermeasures. Significant reductions in the uncertainty of risk prediction are expected to be achieved during the intermediate-term phase. During this period the radiobiological database for effects of HZE particles is expected to be complete and validation of ground-based risk predictions is expected to begin, using the International Space Station. The final phase is expected to yield fully developed biomedical science and technology for radiation risk

mitigation, and to take advantage of scientific breakthroughs expected to lead to practical biomolecular radiation countermeasures.

Proton and heavy-ion beams can be used to acquire the required knowledge in ground-based laboratories. Table I describes some of the areas in which essential information is required. The collection of this information is critically dependent on the availability of high-energy proton and heavy ion accelerators for acquisition of the required data and development of the necessary understanding of physical and biological mechanisms of interaction of HZE particles with living matter. However, only a very small number of accelerators in the world can meet the constraints required to simulate space radiation.

III. SIMULATION OF SPACE RADIATION

The radiation of concern for humans in space consists of protons and HZE particles. Protons are the relevant component of trapped radiation (the main source of radiation exposure in low Earth orbit - LEO, at least at low inclination), they are the main component of SPE events, and they are the most abundant particle in GCR. The trapped radiation and SPE protons have energies up to several hundred MeV. Some heavy elements can originate from the sun, but they generally have much lower energies and intensities relative to the protons and are generally not fully stripped of their electrons. For this reason they are not considered as a primary component of radiation risk.

The relative abundances of GCR particles (9) are shown in Figure 2(a), and typical energy spectra (10), are shown in Figure 2(b). The GCR particles of interest for radiation protection of crews engaged in space exploration range from protons (nuclei of hydrogen) to nuclei of iron; the abundances of heavier elements are orders of magnitude lower. As shown in Figure 2(a), the fraction of GCR constituted by the nuclei of elements heavier than helium is very small; approximately, GCR consist of 85% protons, 14% helium, and 1% heavier particles. Significant numbers of these particles have energies up to several thousand MeV per nucleon.

FIGURE 2

These particles, with energies of several hundred, or even several thousand MeV per nucleon, will suffer nuclear interactions in spacecraft materials. Those interactions can result in fragmentation of the projectile into lighter nuclei proceeding roughly in the same direction, and at approximately the energy per nucleon, of the incident nucleus. They can also result in target fragments; in the case of protons, these are the main concern of nuclear interactions. Projectile fragments will consist of energetic nuclei of all isotopes lighter than the incident particle; similarly, target fragments may consist of nuclei of all isotopes lighter than the

target nucleus. Thus, the radiation that needs to be simulated is not only the primary particles found in space, but also the secondary particles produced by their interactions with matter. The nuclei range from protons to iron, and the relevant energies vary from approximately 50-100 MeV/nucleon to several thousand MeV/nucleon.

The HZE particles are highly penetrating. Ranges in water are shown in Figure 3 for the most abundant components of space radiation. It may be seen that HZE particles at GCR energies can traverse thicknesses equivalent to as much as several meters of water; even at the lowest energies, their range is comparable to human organ dimensions. The LET, resulting from the energy per unit length deposited by these particles in matter, ranges from less than 1 keV/ μm , for the most energetic protons, to 1000 keV/ μm for the slowest iron particles. This range extends well beyond the range for which accurate biological data at low doses and dose rates exist.

FIGURE 3

The HZE nuclei are highly charged and, therefore, very densely ionizing. As a consequence, even though the number of HZE particles is relatively small, they have a significant biological impact that is comparable to that of protons. The relative biological effectiveness (RBE) of HZE particles has been measured for a limited number of end-points. These measured RBE values increase non-linearly as a function of increasing LET in the shaded region, from approximately 30 to approximately 200 keV/ μm , with a peak at approximately 100 keV/ μm . Thus, correlation with the quality factor, Q , used in radiation protection, leads to the significant dose equivalents resulting from exposure to relatively small fluxes of GCR particles.

A relatively small subset of primary space radiation components accounts for a disproportionate fraction of the overall risk when RBE or comparable biological effectiveness criteria are used. An example of such a calculation is shown in Figure 4. In this figure, the average dose-equivalent rate (Sv/yr) from exposure of the eye to space radiation is used as the criterion of risk; other criteria yield similar results. For solar minimum, behind 1, 5 and 20 g/cm² of polyethylene (taken as approximately tissue-equivalent), the seven most abundant GCR nuclei (protons, He, C, O, Mg, Si, and Fe) are found to account for ~90% of the physical and biological effects of GCR radiation.

FIGURE 4

The relative contribution of different components of space radiation risk, using this approximation, can be seen in Figure 5. The dose due to protons dominates for both SPE and GCR, mainly due to their high

fluences. However, when radiation risk is quantified, as is done using dose equivalent for the calculations in Figure 5, the biological significance of the HZE particles becomes apparent, even for SPE (where they continue to be relatively negligible).

FIGURE 5

To a good approximation, space radiation is isotropic, whereas ground-based sources are accelerators delivering beams of these particles in one direction. As a consequence, instruments designed for space need to be either insensitive to the direction of the incident radiation (as, for example, dosimeters) or need to incorporate knowledge of the direction of radiation into their results. When such instruments are studied in a particle beam, it will be frequently necessary to perform measurements for different directions of incidence. Similarly, edge effects may be important on the ground, but need to be excluded for predictions in space geometry.

The dose rate of space radiation is sufficiently low outside of SPE events and traversals of individual cells by single particles are the most important form of energy deposition. The probability that an individual cell will be traversed by more than one particle in a time short compared to the initial chemical phase of radiation action is small. Hence, experiments performed at high dose rates on the ground need to take into account the short-term dose rate dependence of the results in order to extrapolate the data to the space situation. Alternatively, experiments need to be conducted at dose rates comparable to those prevailing in space. However, to the extent that cells or tissues suffer long-term modification (as would be the case in genomic instability), longer term dose-rate effects may need to be studied.

IV. GROUND-BASED FACILITY CHARACTERISTICS

Beams of protons and heavy ions are produced by particle accelerators. The quantities that characterize such beams are: the particle species, given by the atomic mass A and the atomic number Z ; the beam energy, the beam intensity, the beam spot size, and the time structure of the beam.

For high-energy heavy ion beams the parameter of interest is the energy per nucleon, a quantity reflecting the average velocity of the energetic nucleus rather than its kinetic energy. It determines the range and the LET of the beam. It is also desirable for biological studies to have sufficient beam energy to permit so-called “track segment” experiments, where the energy and the LET do not vary significantly within the targeted samples. Many nuclear interactions are not strongly dependent on energy, but the number of

interacting generations in a stopping beam depends on the range. In general, the beam energy on target is less than the beam energy at the extraction port of the accelerator if particle detectors or even significant amounts of residual gas are present in the beam line.

For relevant accelerators and fully stripped particles, the charge-to-mass ratio Z/A determines the maximum momentum and, hence, the maximum energy of the beam which can be accommodated by the bending power of the magnets. The neutral atom, with Z electrons, must be ionized for injection into the accelerator. This ionization becomes progressively more difficult as Z increases, and the yield of injected ions decreases accordingly. Frequently, high Z particles (e.g., iron) need to be accelerated in only a partially ionized state in order to provide adequate intensity. Partially ionized particles will have a smaller charge-to-mass ratio and, hence, a lower beam energy than fully stripped particles.

Most accelerator beams are pulsed. The cycle time of relevant accelerators is of the order of seconds. Each pulse, or “spill” may have further time structure, depending on the intricacies of the acceleration and extraction scheme used. The intensity of accelerator particle beams is generally given as the total number of particles delivered per pulse. However, the particle flux (particles per unit area per unit time), which determines the dose rate, depends on the size of the beam spot. For experiments requiring large beam spots, as would be the case for animal irradiations, the flux goes down and high dose rate experiments become increasingly difficult to perform. The average dose rate will be given by the number of particles per pulse, divided by the beam spot area, times the number of pulses per relevant time interval. The instantaneous dose rate depends on the time structure of each pulse. The sensitivity of experimental systems and also the accuracy of dosimeters and other instruments for instantaneous dose rate effects need to be taken into account when designing accelerator experiments.

Table II illustrates some of these characteristics for three beams used at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory in the United States. The 600A MeV iron beam energy is the minimum energy at which beams can be obtained from this high energy machine, while 10.8A GeV is the maximum energy available. The LET (in tissue) is usually calculated from the energy deposition in a calibrated detector, or from the measured velocity of the identified beam particles. The number of particles per spill is usually measured by beam monitoring instruments.

The flux is calculated as the ratio of dose rate to LET (with appropriate unit conversion factors). The beam spot diameter (estimated from the full width of the observed beam intensity distribution) is fairly typical of a “small” beam spot. In biology experiments, the full beam is generally expanded to an area larger than the target, in order to minimize variations in intensity over the target; for example, in the case of 600A MeV iron, the total number of particles per spill, the measured dose rate and the measured LET lead to an equivalent area, containing the entire beam distribution, of approximately 12.3 cm^2 . The table also shows

the number of beam hours required for characterization and dosimetry, a non-trivial overhead to be considered in estimating useful numbers of beam hours.

The minimum dose required for exposures at the AGS during the measurements used for Table II was 0.05 Gy; other dose response curves may require exposures to several Gy. A calculation of dose rate for a larger beam spot, of 20-cm diameter, is shown in Table III for both the AGS and parameters available for the HIMAC accelerator in Chiba, Japan. The larger beam spot leads to a significantly reduced dose rate; however, the dose rate is still within the limits required by the majority of experiments. Only experiments requiring exposures of the order of 100 Gy, constrained in other ways (e.g., anaesthesia of animals, cell oxygenation), may find difficulty with such dose rates.

In addition to the accelerator beam characteristics, the laboratory infrastructure available at a given accelerator laboratory must be able to accommodate radiobiological as well as physics experiments. A list of the most basic essential elements is given in Table IV. The availability of the accelerator facility for such work during the year is also an important consideration, since most existing accelerator facilities have been set up for other uses, including high-energy physics, nuclear physics and radiation therapy.

Finally, the long-term prospects for continued availability of the facility are an important consideration since experiments and experimental programs often have to be planned many years in advance. An estimate of the likely requirements for a program of the type outlined above is shown in Figure 6. This estimate is based on the author's evaluation of the recommendations of several workshops and study groups over the past several years. The number of beam hours is limited at the low end by the requirement to maintain the vitality of the field: first-rate scientists will be reluctant to embark on research and development programs without reasonable access to the required facilities. At the high end, beam time requirements are limited by beam availability and the size of the scientific community that can be supported. Other examinations of the required beam time, using different assumptions, have been made by several groups. Their recommendations are not significantly different, pointing toward a need for approximately 1000 hours of beam time per year at different facilities in order to have a viable program.

FIGURE 6

V. ANALYSIS OF GROUND-BASED FACILITIES

The facilities available for simulation of space radiation are severely limited. While proton beams can be produced at many facilities, currently only the Loma Linda University Therapy Proton Synchrotron facility in Loma Linda, California, is equipped to handle the sophisticated biological research described above.

The situation for HZE simulation is even more constrained. There are only 4 facilities that can be considered for practical use. One of these, the heavy ion accelerator SIS at the GSI research institute in Darmstadt, Germany, is in high demand by the German nuclear physics community. In addition, use of the facility for cancer therapy started in December, 1997 and the facility can be considered unavailable for all intents and purposes. The HIMAC facility at the National Institute of Radiological Sciences in Chiba, Japan, has a moderate amount of beam time available and an active collaboration between the NASA Space Radiation Health Program and this laboratory has been under way since 1995.

The other two facilities for HZE delivery are the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) in Long Island, New York, and the Booster Synchrotron, used as an injector in the accelerator chain leading to the AGS. These accelerators are currently operated by the high energy and nuclear physics programs of the United States Department of Energy (DOE), and NASA purchases beam time for several experimental campaigns per year.

A schematic diagram of the BNL accelerators is shown in Figure 7. Protons originate with the 200 MeV LINAC injector and HZE particles originate in one of the two Tandem Van de Graaffs, from where they are transported into the Booster synchrotron. The Booster synchrotron then accelerates either protons or heavy ions for injection into the AGS, where they are accelerated further for injection into the Relativistic Heavy Ion Collider (RHIC). Currently, experimenter access to the Booster Synchrotron is not available. A suitable irradiation facility, the Booster Applications Facility (BAF), has been designed; the proposed beam line, with capability of switching between 3 experiments, is shown schematically in the inset of Figure 7.

FIGURE 7

In order to better understand the extent to which even these four facilities meet the scientific requirements for simulation of space radiation, we have divided the components of space radiation and its nuclear interaction products in matter into five groups of particles: protons (including deuterons and tritons), alpha particles to represent helium nuclei, nuclei with atomic number between 3 and 10 (e.g., C, N, O, Ne), intermediate nuclei (e.g., Si, Mg) with $11 \leq Z < 20$, and heavy nuclei (typically, Fe) with $21 \leq Z \leq 28$. For each group, differential spectra of dose equivalent per logarithmic interval of energy per nucleon and

integrated dose equivalent up to energy per nucleon E were calculated for skin and for blood-forming organs (BFO) behind 5 g/cm^2 of aluminum, a representative thickness of material for many spacecraft situations.

The differential spectra for skin are shown in Figure 8 (a) and the integral spectra are shown in Figure 8 (b). Near the body surface most HZE particles have been slowed down slightly to lower energy/nucleon than in free space. Relatively abundant protons and alpha particles are produced at very low-energy by nuclear interactions of all primaries in the aluminum and are not shown in the figure. Light HZE particles consist of primary GCR components as well as projectile fragments from nuclear interactions; this contributes to the lower energy part of the spectrum. High-velocity (high energy/nucleon) particles that have been slowed down will also have higher LET and, therefore, higher Q in most cases. Only particles incident with LET greater than $\sim 200 \text{ keV}/\mu\text{m}$ will be in the “overkill” RBE regime and will have a smaller value of Q .

FIGURE 8

In Figure 9 we consider results for the differential spectra (a) of dose equivalent per logarithmic interval of energy per nucleon and integrated dose equivalent (b) up to energy per nucleon E for blood-forming organs (BFO) behind 5 g/cm^2 of aluminum. At 5-cm depth into the body, the heaviest group of HZE particles has been substantially stopped and no longer is the most effective constituent. The low-energy protons and alpha particles produced by nuclear interactions of all primaries in the shielding and the BFO now contribute substantially to the calculated dose-equivalent. Light HZE particles are still at relatively high-energy and relatively low-LET and the intermediate HZE particles dominate the dose-equivalent spectrum.

FIGURE 9

The energy ranges covered by the four accelerators considered here are shown as bars, labelled with the appropriate acronym. It may be seen that the high energy part of the spectrum contributes significantly to the dose equivalent; in the case of iron, almost 75% of the contribution is at energies above 600A MeV.

VI. CONCLUSIONS

From the preceding results, it can be concluded that accelerators capable of simulating space radiation must satisfy the following constraints:

- the 7 most abundant GCR nuclei (protons, He, C, O, Mg, Si, and Fe) need to be studied to account for ~90% of the physical and biological effects of GCR radiation.
- required beam energies are in the range of 50-1000 MeV for protons and 50 to several thousand MeV/nucleon for HZE particles;
- the highest energies are required, not only to study the effects of these particles, but to ascertain the effect of nuclear interaction products and to have enough range to perform track segment animal irradiation
- dose rates must be adequate to perform cellular and animal radiobiology experiments (i.e., relatively large areas need to be irradiated uniformly at dose rates compatible with sample constraints
- the infrastructure for large scale, modern biological experimentation (e.g., molecular biology, transgenic animals) must be available.

Together, the facilities (BAF, AGS, HIMAC, SIS) discussed above have the capability to provide the required data in a reasonable time. However, given the magnitude of necessary beam time and the pressures that limit beam delivery for space radiation research at existing facilities, construction and operation of the BAF facility remains a critical and essential element of any attempt to resolve the space radiation problem in an efficient and timely manner.

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FIGURE CAPTIONS

Figure 1. The NASA Space Radiation Health Program

Figure 2. The distribution of GCR particles in atomic number (charge) and energy. The HZE particles relevant for space radiation risk extend up to iron ($Z=26$ in Fig. 1a) and have energies up to several thousand MeV/nucleon (Fig. 1b).

Figure 3. Linear energy transfer (LET) as a function of range in water for selected HZE particles. Lines of constant velocity (expressed as energy per nucleon) have been indicated for each particle. The region corresponding to particles of maximum relative biological effectiveness (RBE) has been shaded.

Figure 4. Average dose-equivalent rate (Sv/yr) from exposure of the eye to space radiation, at solar minimum, behind 1, 5 and 20 g/cm² of polyethylene (approximately tissue-equivalent). The most significant components are shown in the inset.

Figure 5. Relative contribution of different components of space radiation to risk estimation.

Figure 6. Estimated requirements for use of proton and heavy ion beams to simulate space radiation.

Figure 7. Schematic diagram of the proposed Booster Application Facility (BAF) at Brookhaven National Laboratory in Upton, NY.

Figure 8. (a) Differential spectra of dose equivalent per logarithmic interval of energy per nucleon and (b) the integrated dose equivalent up to energy per nucleon E for the skin behind 5 g/cm² of aluminum.

Figure 9. (a) Differential spectra of dose equivalent per logarithmic interval of energy per nucleon and (b) the integrated dose equivalent up to energy per nucleon E for the BFO behind 5 g/cm² of aluminum.

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Table I. Areas of study using proton and heavy-ion beams to simulate space radiation

- Shielding design tools and radiation transport calculations, including:
 - nuclear & atomic interaction data for elements and mission specific materials
 - biological characterization of radiation fields
 - radiation analysis of baseline exploration mission
- Molecular and cellular biology research for protons and high energy HZE
 - uncertainty in RBE-dependent components of risk model
 - mechanisms of genomic instability
 - unknown effects identified or ruled out
- Studies with transgenic animals and cells in culture to establish range of risk in relation to age, gender, stress (susceptibility, space factors, direct prior exposure to other agents, etc.)
- Probability of behavioral/ neurological functional impact
 - functional brain cell survival
 - functional changes in brain cell metabolism (PET, MRI)
 - task performance
- Probability of germ cell effects
- Countermeasures
 - understand mechanisms, including age and time (pre- or post- irradiation) dependence
 - biodosimetry/biomarkers of radiation susceptibility and postflight risks
 - radiosensitivity diagnostics and crew selection
 - post-exposure genetic techniques (enhance repair/eliminate damage)
 - chemical and biological modifiers (cell cycle control, modifiers of gene expression, apoptosis, cytokines, etc.)

Table II. Characteristic parameters for several beams at the Brookhaven National Laboratory Alternating Gradient Synchrotron¹

	⁵⁶ Fe 600A MeV	⁵⁶ Fe 1000A MeV	¹⁷⁹ Au 10.8A GeV
Beam Energy (MeV/nucleon)			
Extracted	610+/-10	1087	10780
On Target	565+/-10	1060	
Measured LET (keV/μm)	177	148	1445
Particles/spill			
Maximum	1.4 x 10 ⁸	1.7 10 ⁸	1.4 10 ⁵
Minimum	6.5 x 10 ⁶	1.7 10 ⁷	
Spill rate per min	30	30	20
Spill length (msec)	500	500	1000
Beam spot diameter (cm)	7.5 - 9	7.5 - 9	7.5
Measured Dose/rate (Gy/min)			
Maximum	10	9.0	0.15
Minimum	0.45	0.9	
Flux (particles/cm ² /sec)			
Maximum on target	5.9 x 10 ⁵	6.3 x 10 ⁵	1080
Minimum on target	2.6x 10 ⁴	6.3 x 10 ⁴	
Minimum dose exposure (Gy)	0.05	0.05	0.1
No of hours for beam characterization and dosimetry	7	16	24

¹data provided by Dr. Marcelo Vazquez, Senior Liaison, Brookhaven National Laboratory

Table III. Beam characteristics and dose rates calculated for a 20-cm diameter beam spot and typical accelerator beams.

HIMAC Biology Port:

Particle Z		Energy Range (MeV/nucleon)	Particles/spill	Dose Rate (Gy/min)	
				$\dot{D}(E_{min})$	$\dot{D}(E_{max})$
He	2	100 - 230	1.2×10^{10}	3	2
C	6	100 - 430	2.0×10^9	5	2
N	7	100 - 400	1.7×10^9	5	2
O	8	100 - 400	1.2×10^9	5	2
Ne	10	100 - 600	8.7×10^8	6	2
Si	14	100 - 600	4.4×10^8	6	2
Ar	18	290 - 500	2.7×10^8	3	2

AGS Biomedical Beam

Fe	26	565 ± 10	1.40×10^8	4	
Fe	26	1060	1.67×10^8		4

Table IV. Ground-based accelerator laboratory infrastructure requirements.

- Dosimetry and beam characterization
- Logistics (shipping, travel, training, safety, etc.)
- Computation, data analysis and archiving
- Control (Co-60, x-ray) and irradiation facilities
- Laboratory and office space, phones, faxes, etc.
- Molecular biology laboratory
- Large cell culture facility w/flow cytometry
- AAALAC (or equivalent)-accredited animal facility (rodents)

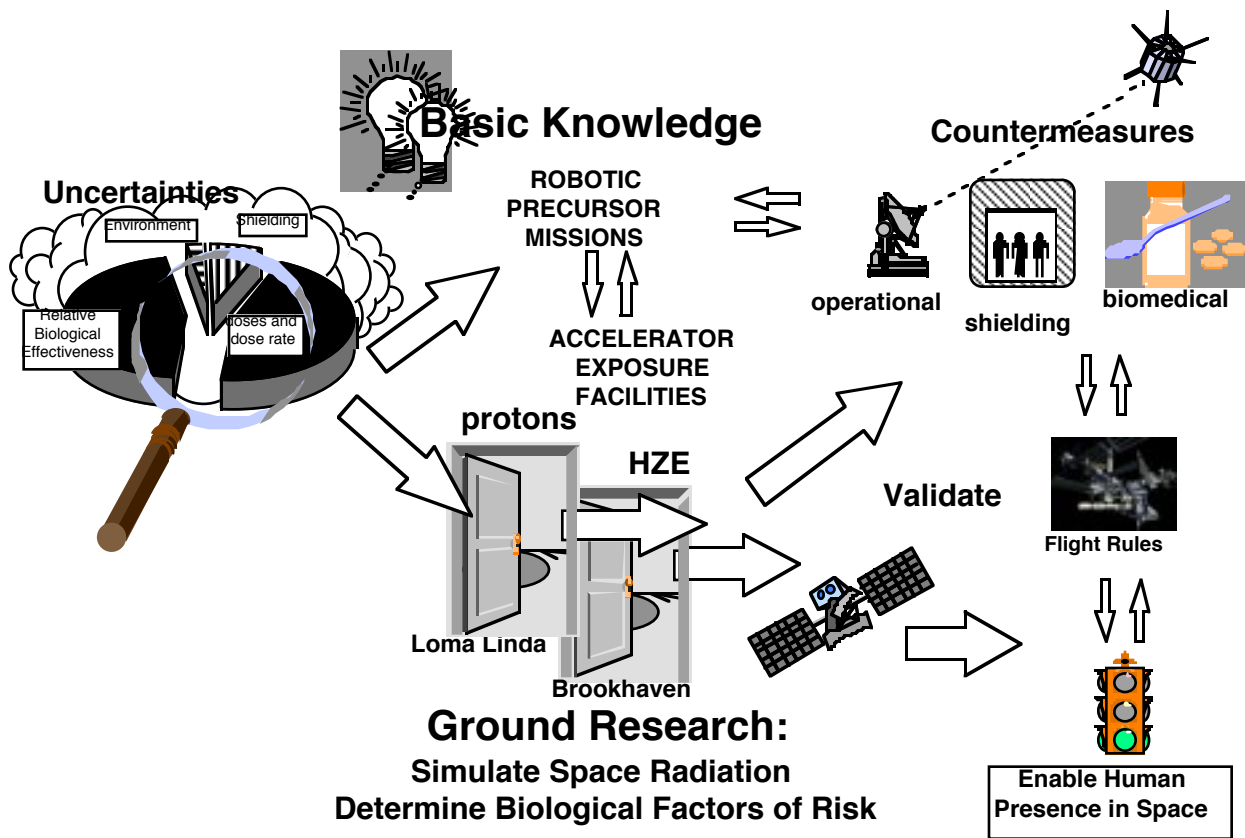


Figure 1. The NASA Space Radiation Health Program

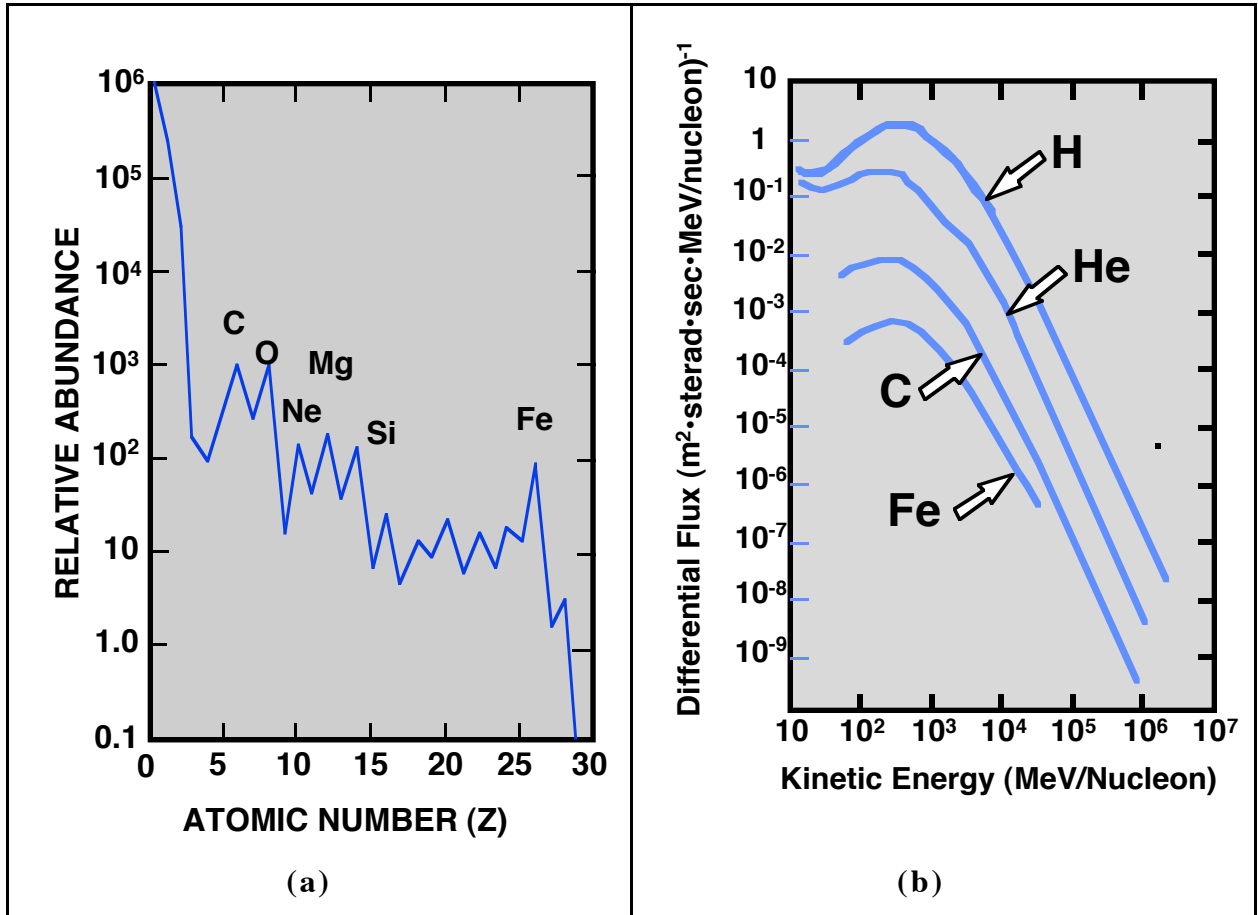


Figure 2. The distribution of GCR particles in atomic number (charge) and energy. The HZE particles relevant for space radiation risk extend up to iron ($Z=26$ in Fig. 2a) and have energies up to several thousand MeV/nucleon (Fig. 2b).

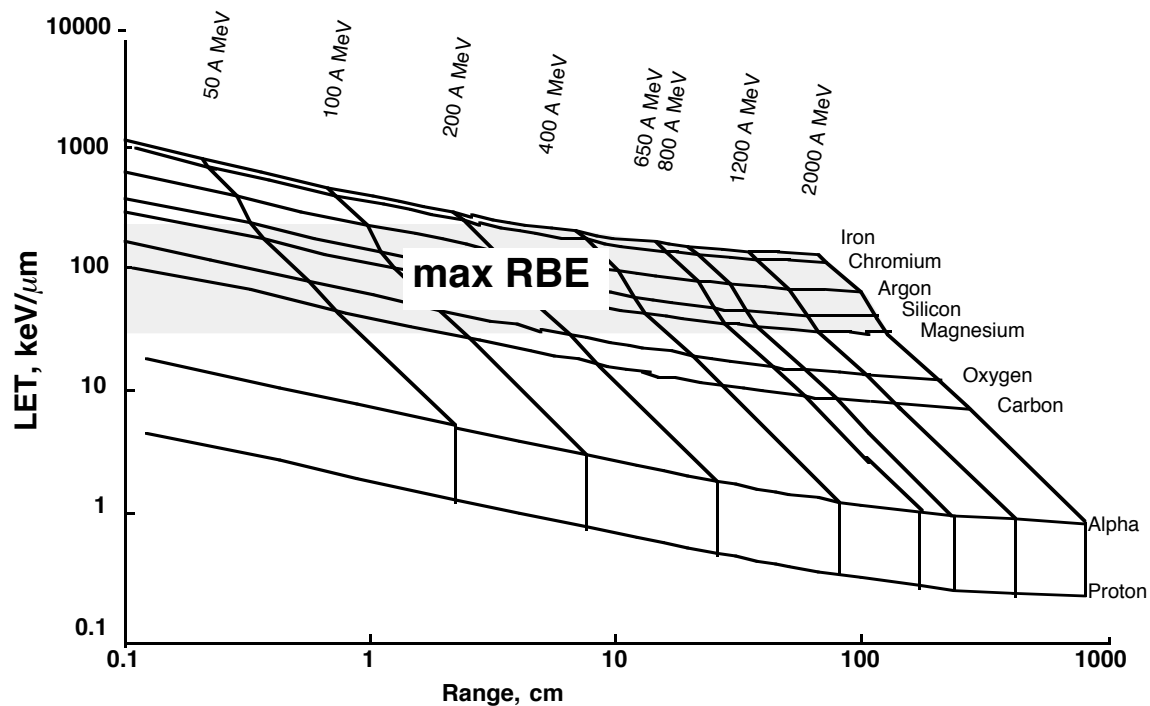


Figure 3. Linear energy transfer (LET) as a function of range in water for selected HZE particles. Lines of constant velocity (expressed as energy per nucleon) have been indicated for each particle. The region corresponding to particles of maximum relative biological effectiveness (RBE) has been shaded.

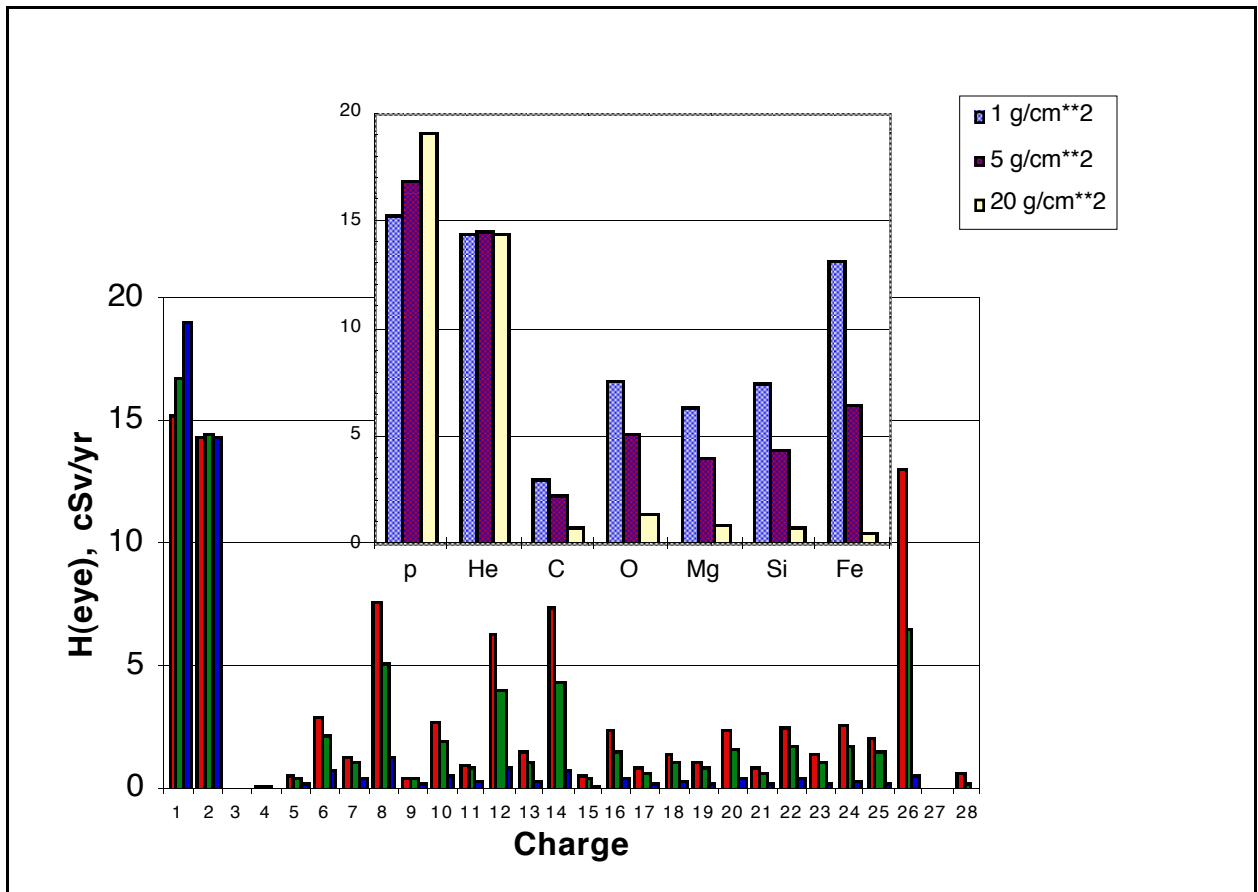


Figure 4. Average dose-equivalent rate (Sv/yr) from exposure of the eye to space radiation, at solar minimum, behind 1, 5 and 20 g/cm² of polyethylene (approximately tissue-equivalent). The most significant components are shown in the inset.

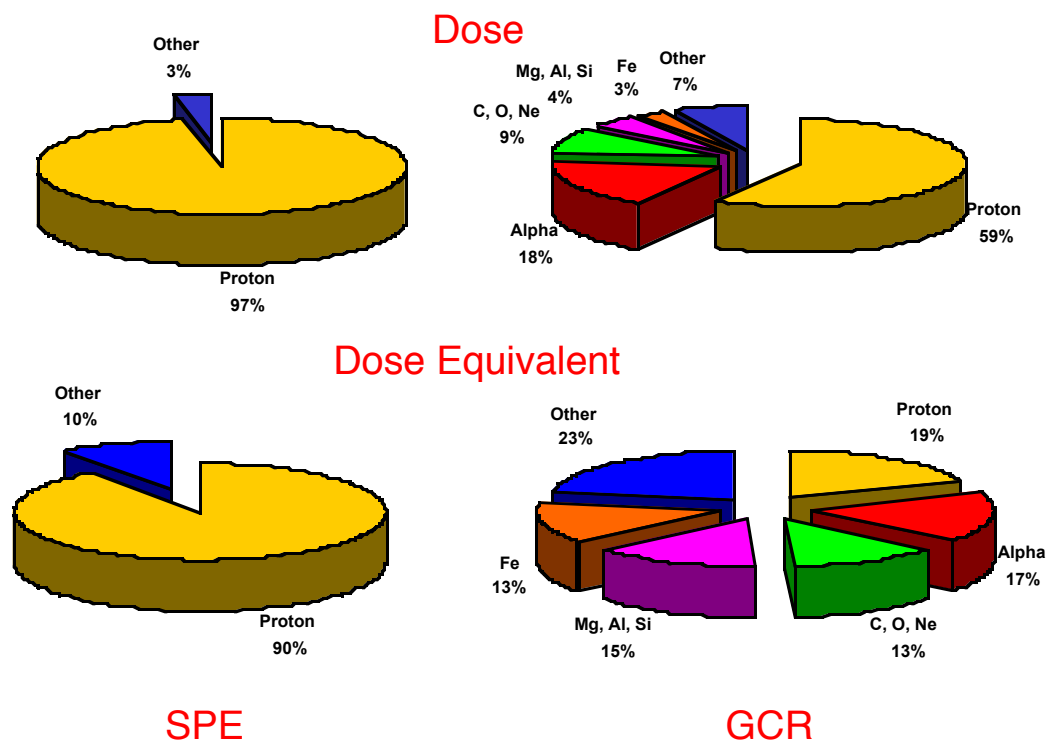


Figure 5. Relative contribution of different components of space radiation to risk estimation.

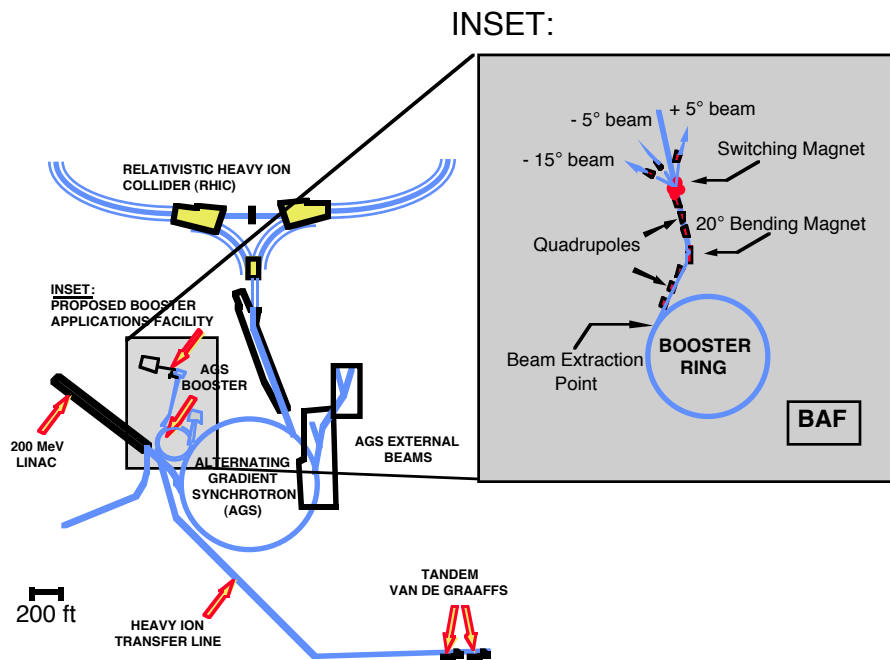
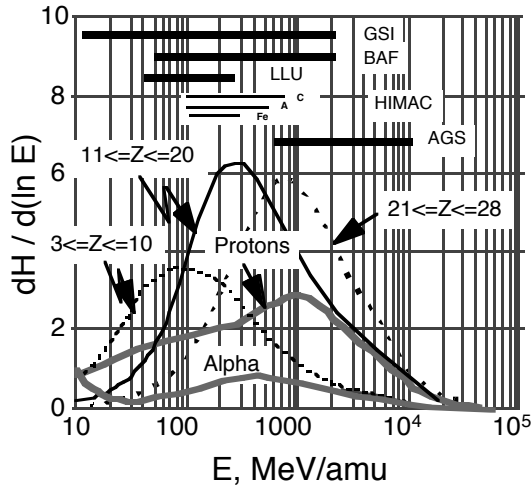
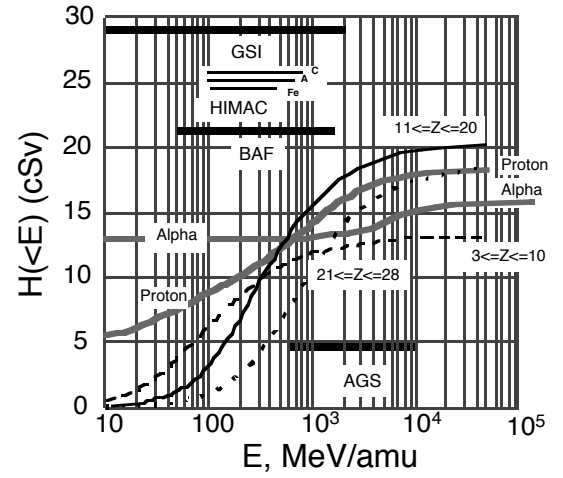


Figure 7. Schematic diagram of the proposed Booster Application Facility (BAF) at Brookhaven National Laboratory in Upton, NY.

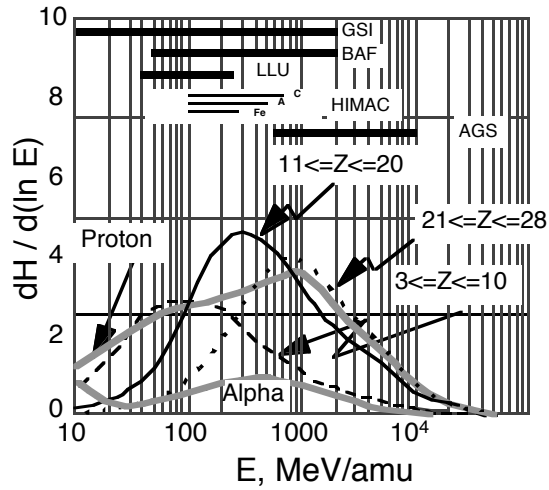


(a)

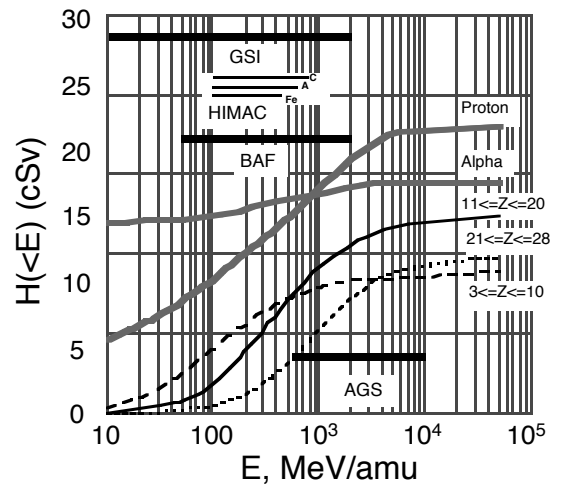


(b)

Figure 8.(a) Differential spectra of dose equivalent per logarithmic interval of energy per nucleon and (b) the integrated dose equivalent up to energy per nucleon E for the skin behind 5 g/cm^2 of aluminum.



(a)



(b)

Figure 9. (a) Differential spectra of dose equivalent per logarithmic interval of energy per nucleon and (b) the integrated dose equivalent up to energy per nucleon E for the BFO behind 5 g/cm^2 of aluminum.